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A Radio Outburst Nearly Coincident with the Large X-ray Flare from Sgr A* on 2002-10-03

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ABSTRACT

A large radio outburst from Sgr A* was observed during the VLA weekly monitoring program at 2 cm, 1.3 cm and 7 mm, nearly coincident with the brightest X-ray flare detected to date with the XMM-Newton X-ray Observatory on 2002-10-03. The flux density of 1.9±0.2 Jy measured at 7 mm exceeds the mean value (1.00±0.01 Jy) by a factor of ~ 2, one of the two highest increases observed during the past three years (June 2000-October 2003), while less significant increases in flux densities were observed at 1.3 cm and 2 cm. The radio observation started 13.5 hrs after the onset of the X-ray flare (which had occurred over a 45 min duration) and continued for 1.3 hrs. During the observation, there was no significant ($< 3\sigma$) change in the radio flux densities at all the three wavelengths, indicating that the radio outburst varied on a timescale of $>$ 1hr. A spectral index of $\alpha = 2.4^{+0.3}_{-0.6}$ ($S \propto \nu^{\alpha}$) was derived for the outburst component, consistent with an optically thick nonthermal synchrotron source. These results suggest that energetic electrons responsible for the radio outburst might be produced via a process associated with the X-ray flare, then transported to large radii, producing the observed radio outburst. The observation is the first evidence for a correlated variation in the radio and X-ray emissions from Sgr A*.

Subject headings: accretion, accretion disks – black hole physics – galaxies: active – Galaxy: center – radio continuum: galaxies

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1. Introduction

Radio "flares" or outbursts (hereafter) on a timescale of a few days to weeks have been observed at short wavelengths from a few centimeters to 1 mm from Sgr A*, the compact radio source in the Galactic Center (Zhao et al. 1992; Wright & Backer 1993; Miyazaki, Tsutsumi & Tsuboi 1999; Zhao, Bower & Goss 2001; Zhao et al. 2003; Herrnstein et al. 2003). Radio observations have shown variations as short as a few hours (Bower et al. 2002). With the *Chandra* and *XMM-Newton* observatories, X-ray flares with shorter variation time ($\sim$ 1 hr) have been frequently observed from the direction of Sgr A* over the past two years (Baganoff et al. 2001; Baganoff 2003; Goldwurm et al. 2003; Porquet et al. 2003). Because both radio and X-ray emissions are presumably produced close to the black hole, where energetic electrons responsible for the emissions are produced due to dissipation of the gravitational energy of the accreting plasma, the lack of correlated variation between radio and X-ray emission poses a number of theoretical challenges (Baganoff 2003). Recently, SgrA* has been detected in the IR band showing the variation in flux density on two timescales: (1) a few days to a week similar to that of the radio outbursts (Ghez et al. 2003b) and (2) $\sim$1hr for the IR flares (similar to X-ray flares) (Genzel et al. 2003).

On 2003-10-03, a giant X-ray flare from Sgr A* was detected with a peak luminosity 160 times higher than the quiescent value (Porquet et al. 2003). No X-ray flare with such a high luminosity has been previously detected. With the high sensitivity of *XMM-Newton*, it was shown that the flare was variable on a time scale of 200 seconds, corresponding to an emission region no larger than $5r_S$, where $r_S = 1.2 \times 10^{12}$ cm is the Schwarzschild radius of the black hole with a mass of $4 \times 10^6\, M_\odot$ (Ghez et al. 2003a). Moreover, the flare has a soft photon spectrum with an spectral index of $\Gamma = 2.5 \pm 0.3$, distinguishing itself from other relatively weaker and more frequent X-ray flares with $\Gamma = 1.3^{+0.5}_{-0.6}$ (Baganoff 2003).

Coincidentally, one observation of the weekly VLA monitoring program was carried out $\sim$0.5 day after the X-ray observation and a radio outburst was detected at 7 mm. In this letter, we report detailed properties of the radio outburst on 2002-10-03. The radio observations in the epochs close to the other weaker X-ray flares are also presented.

2. Observations & Calibrations

The observations and data reduction for the VLA weekly monitoring program are discussed and reported by Herrnstein et al. (2003). On 2002-10-03, Sgr A* was observed at 2 cm, 1.3 cm and 7 mm with a total BW of 100 MHz. The total observation time was 2 hrs including observations of a primary calibrator 3C 286, and QSOs 1741-312, 1817-254,

1730-130 for phase and amplitude corrections. Scans on calibrator 1817-254 were interleaved between Sgr A*'s scans ($\sim$ 5 mins each) at the three observing wavelengths. Three scans were made on both Sgr A* and 1817-254 at each wavelength over a period of 1.3 hrs.

The absolute flux scale was determined from 3C 286. The final fractional uncertainties from a conservative estimate for the day-to-day variability are 6.1%, 6.2% and 9.2% at 2 cm, 1.3 cm and 7 mm, respectively (Herrnstein et al. 2003). The intra-hour variability of 1817-254 appeared to be small during the observation on 2002-10-03. Any variation was $<$ 5% during the 1.3 hr at 7 mm and $<$ 2% at 2 and 1.3 cm. In addition to measurements on 2002-10-03, measurements of radio flux densities at the three wavelengths corresponding to other X-ray events with a change in amplitude by a factor of 20 or greater were also made.

3. Results

Figure 1 shows measurements of flux densities at 2 cm, 1.3 cm and 7 mm obtained from the weekly monitoring program (Herrnstein et al. 2003) one month before and after the 2002-10-03 X-ray event. The flux density at 7 mm showed at least a 4σ increase on 2002-10-03. Variations in flux density at 1.3 cm and 2 cm were 3σ and $< 1\sigma$, respectively.

The sampling period of the VLA monitoring program was about 1 week. The measurements a week before and after the outburst showed that the flux densities were consistent with the mean value of the flux densities averaged over the past three years (June 2000 - October 2003; see Table 1). Therefore, the timescale of the radio outburst at 7 mm must be less than two weeks for this event. The X-ray light curve observed with XMM-Newton showed a larger flare (160 x) (Porquet et al. 2003). The X-ray observation started at UT 7^h 18^m 8^s on 2002-10-3 (Porquet 2003, private communication). The X-ray flare onset occurred at UT 10^h 5^m and lasted for about 45 mins. Our VLA observation started on 2002-10-03 at 23^h 30^m, about 13.5 hrs after the onset of the X-ray flare, and ended on 2002-10-04 at 0^h 45^m with three 5min scans on Sgr A* and the calibrator. Based on the three measurements averaged on each scan over a 1.3 hr, we found that there were no significant variations in flux density ($< 3\sigma$) during the VLA observation at all the three observing wavelengths. A time scale for significant change ($> 3\sigma$) in radio flux density was likely greater than 1 hr for the radio outburst.

Table 1 summarizes the radio property for the radio outburst corresponding to the X-ray flare on 2002-10-03. The mean radio flux densities of $<$ S $>$ (Column 2) and the total flux densities S_t observed on 2002-10-03 (Column 3) for the three observing wavelengths are given in Column 2 and 3 respectively. The flux densities for the outburst component

($\Delta S = S_t - < S >$) are given in column 4. The spectral index of $\alpha = 0.71 \pm 0.11$ ($S \propto \nu^\alpha$) derived from the total flux densities appears to be significantly greater than the spectral index of 0.2±0.02 derived from the mean flux densities observed over the past three years (June 2000 - October 2003). The increase in the spectral index of the 2002-10-03 event is consistent with the general correlation between spectral index and flux density at 7 mm (Herrnstein et al. 2003). A spectral index of $\alpha \approx 2.4^{+0.3}_{-0.6}$ was derived for the outburst component, which is consistent with an optically thick, nonthermal synchrotron source.

In addition to the 2002-10-03 X-ray event Fig. 2 shows a fraction of radio light curves covering a period ±30 d for each of the other three X-ray flares (a factor of 20 greater than a quiescent level) detected in the past three years.

For the 2000-10-27 X-ray flare observed with Chandra (Baganoff et al. 2001), the peak X-ray flux was a factor of 45 greater than the quiescent level. Radio observations made three days before and four days after the X-ray event showed no significant increase in radio flux density measured in the two epochs close to this large X-ray event. However, the flux densities measured 9 days after the X-ray event showed $\sim 3\sigma$ increase in the radio flux densities at 2 and 1.3 cm and $\sim 2\sigma$ at 7mm.

For the 2001-09-04 event, the beginning phase of this X-ray flare was observed with XMM-Newton (Goldwurm et al. 2003); the amplitude of this flare was a factor of 20 greater than the quiescent level. There were two observations at radio wavelengths carried out three and four days before the X-ray event. The flux densities were $2 - 3\sigma$s higher than the mean flux density at all the three observing wavelengths. The flux densities measured five days after the X-ray event appeared to be consistent with the mean flux densities.

During the May 2002, there was a multi-wavelength campaign that coincided with 100 hrs of Chandra observations. During that period, the Chandra observations showed that flares with a factor of 5 greater in amplitude occurs once every day and larger flares with a factor of 10 greater occurs once every two days (Baganoff 2003). A large flare (20x) occurred on 2002-05-29. However, the radio measurements made 3 days before and 4 days after the 2002-05-29 event showed no significant variations in flux density. There were also no significant variations observed at 7, 3 and 1.3 mm using VLBA, ATNF, and SMA, respectively, in response to these multiple small X-ray flares (Baganoff 2003).

The lack of correlation in radio flux density at wavelengths ranging from 2 cm to 7 mm with the weaker X-ray flares has been puzzling. The weekly VLA monitoring program appeared to be not sensitive to the weaker X-ray flares. However, the large X-ray flare on 2002-10-03 appeared to be special in many aspects. In addition to a high luminosity and softer X-ray spectrum, a large radio outburst at 7mm was detected within the same

day. Based on the fact that we only detected two large (2x) radio outbursts at 7mm from observations of 121 epochs weekly sampled over the past 3yr period between June 2000 to October 2003, the probability of detecting such a large (2x) radio outburst within a time interval of Δt appears to be $P_R \sim 0.01 \frac{\Delta t}{\Delta t_{sampling}}$, where $\Delta t_{sampling} \sim 1$wk, the radio sampling interval. On the other hand, during the past three years overlapping with the period of VLA monitoring program, observations of a few hundred hours were carried out at X-ray with both Chandra and XMM-Newton to search for X-ray flares, but to date only one large (160x) X-ray flare has been detected. Considering the typical duration of $\Delta t_X \sim 1$hr for the X-flares, then the detection probability of a large flare (160x) within Δt appears to be $P_x < 0.01 \frac{\Delta t}{\Delta t_X}$. A large uncertainty in estimate of P_X is owing to the sparse observations at X-ray and a large chance to have a stellar X-ray transient in the large XMM-Newton beam. However, if both the radio and X-ray events were randomly produced from two independent processes, then the probability of detecting large radio and X-ray events within a time-scale of the radio outburst Δt_R would be $P = P_R \times P_X < 0.0001 \frac{\Delta t_R^2}{\Delta t_X \Delta t_{sampling}}$. Based on our observations, the time-scale on the radio outburst is well constrained in a range of $1\text{hr} < \Delta t_R \leq 1\text{wk}$. For $\Delta t_R \leq 1$wk, the probability is <2 %. For $\Delta t_R \sim$a few days, a reasonable guess for the time-scale of the radio outburst, then the probability would be 0.1 - 0.3%. Statistically, we have a good confidence to reject the hypothesis that the two events were produced from two independent random processes. The two large events observed at radio and X-ray appeared to be related.

Since the radio outburst component of the 2002-10-03 event had a spectral index of $2.4^{+0.3}_{-0.6}$, it is likely that the large X-ray flare was associated with an optically thick, nonthermal synchrotron component in Sgr A*. With an upper limit of 8 km s^{-1} for the intrinsic proper motion of Sgr A* determined from VLBI measurements, a lower limit on the mass of Sgr A* of 4×10^5 $M_\odot$ (Reid etal 2003) is placed. This limit along with the compactness of Sgr A* with an intrinsic size of 0.24 mas or 24 r_S(Bower et al. 2003) suggests that Sgr A* is very likely associated with the putative supermassive black hole at the Galactic center. If the radio outburst component was confined within $< 24 r_S$ from the black hole, then the X-ray flares must arise from the inner region of the accretion flow near the event horizon of the SMBH rather than from star-star collision (Baganoff et al. 2001) or from the heated part of the disk via star-disk interaction (Nayakshin et al. 2003).

4. Discussion

A radio outburst observed at 7 mm coinciding in about 0.5 day with the most luminous X-ray flare appeared to show an intimate relation between the two events. The significant

variability on a timescale of 200s observed during the X-ray flare indicates that the size of the X-ray emitting region is about $5\mathrm{r_S}$. The observed optically thick nonthermal outburst component was likely produced from a region with a size $> 5\mathrm{r_S}$ as suggested by the following facts.

The lack of significant variation in flux density during the radio observation of the outburst suggests that its variation time scale should be longer than one hour, which is about twenty times greater than the variation timescale of the X-ray flare.

If the outburst component is indeed a self-absorbed nonthermal synchrotron source with a turnover frequency $\nu_m > 43$ GHz and a peak flux density $\mathrm{S_m} \sim 0.86\mathrm{Jy}(\nu_\mathrm{m}/43\ \mathrm{GHz})^{2.5}$. The turnover frequency is likely $\nu_\mathrm{m} \sim 300\mathrm{GHz}$ (or $\lambda_m \sim 1\mathrm{mm}$) based on previous observations of Sgr A* at submillimeter wavelengths (Zhao et al. 2003; Serabyn et al. 1997). The brightness temperature of the outburst component can be calculated:

$$\mathrm{T_B} \approx 3.2 \times 10^{11}\mathrm{K} \left(\frac{\nu_\mathrm{m}}{43\mathrm{GHz}}\right)^{0.5} \left(\frac{\mathrm{D}}{8\ \mathrm{kpc}}\right)^2 \left(\frac{5\mathrm{r_S}}{\mathrm{d}}\right)^2, \tag{1}$$

where D is the distance to Sgr A* and d is the diameter of the source. The brightness temperature could break the inverse Compton scattering limit for self-absorbed synchrotron source (Readhead 1994; Sincell & Krolik 1994) if $\nu_m \sim 300$ GHz and $\mathrm{d} \sim 5\ \mathrm{r_S}$. If the onset of the radio outburst indeed arose from the X-ray region with a size of $\mathrm{d} \sim 5\ \mathrm{r_S}$, the outburst component must expand substantially to reach a size of $\mathrm{d} \sim 24\ \mathrm{r_S}$ as observed with VLBI(Bower et al. 2003) so that a drastic energy loss from the self-synchrotron inverse Compton scattering (SSC) lasted only for a short period, perhaps, of ∼1 hr as suggested by the duration of the X-ray flare.

On the other hand, for a spherical, optically thick synchrotron source, the magnetic field (B) can be estimated from the source angular size ($\theta = \frac{\mathrm{d}}{\mathrm{D}}$), $\mathrm{S_m}$ and ν_m (Marscher 1983):

$$\mathrm{B} \approx 0.035\mathrm{G} \left(\frac{8\ \mathrm{kpc}}{\mathrm{D}}\right)^4 \left(\frac{\mathrm{d}}{5\mathrm{r_S}}\right)^4 \left(\frac{\nu_\mathrm{m}}{43\mathrm{GHz}}\right)^5 \left(\frac{\mathrm{S_m}}{1\mathrm{Jy}}\right)^{-2} \approx 0.045\mathrm{G} \left(\frac{8\ \mathrm{kpc}}{\mathrm{D}}\right)^4 \left(\frac{\mathrm{d}}{5\mathrm{r_S}}\right)^4. \tag{2}$$

For $\mathrm{d} \sim 24\ \mathrm{r_S}$, the typical size of Sgr A* as measured with VLBI at 7mm, the inferred B∼ 24 G is consistent with the characteristic magnetic field near the black hole as suggested in theory (Liu & Melia 2002b). For B∼ 24 G, the synchrotron cooling time at 43 GHz of ∼0.5 d is inferred, which is consistent with our observations of no significant variations in flux density at 7mm within the observing interval of 1 hr.

Thus, the 7 mm radio outburst was likely produced at a relatively large size scale with respect to the source size of the X-ray flare. Given that the radio outburst was observed about 13.5 hrs after the onset of the X-ray flare, it is reasonable to suggest that the electrons

producing the radio outburst were energized (Yuan et al. 2003) via a process associated with the X-ray flare and transported to larger radii via a diffusion process (Liu & Melia 2002b; Zhao et al. 2003) if not a collimated jet (Falcke et al. 1993; Yuan et al. 2002). The correlation between radio spectral index and 7mm flux density observed with the VLA (Herrnstein et al. 2003) and the frequent X-ray flares observed with Chandra (Baganoff et al. 2001; Baganoff 2003) may also suggest that the nonthermal electrons responsible for the overall radio emission from Sgr A* are probably energized via a similar process.

To justify the above scenario for correlated variation between radio and X-ray emissions, the energetic electrons diffusing outward to a large radii must contain enough energy in order to sustain the radio outburst for a few days. Because the X-ray flare was probably produced via SSC in the model, to avoid drastic inverse Compton losses, the magnetic field energy density must be larger than the photon energy density near the black hole. If the nonthermal electrons were still in energy equipartition with the magnetic field, the energy flux associated with the escaping nonthermal electrons should be larger than the energy flux of the photons. The X-ray luminosity between $2-10$ keV during the flare was about 4×10^{35} erg s^{-1}. Given the softness of the X-ray emission, the total X-ray luminosity could be around 10^{36} ergs s^{-1}. Thus, the total energy X-ray emission produced during the X-ray flare was about 10^{40} ergs. The energy carried by nonthermal electrons during the X-ray flare was then about 10^{40} ergs, which could sustain an outburst component of 0.86 Jy at 7 mm for a few days.

5. Conclusions

One of the two strongest radio outbursts observed over the past three years appears to be related to the largest X-ray flare to date which was observed on 2002-10-03. The correlation between the strong emissions at X-ray and radio suggests that the radio outbursts are powered via an electron acceleration process during the X-ray flare. Our observations and analysis are consistent with the hypothesis that the X-ray flare originates from self-synchrotron inverse Compton scattering process close to the supermassive black hole at the Galactic center.

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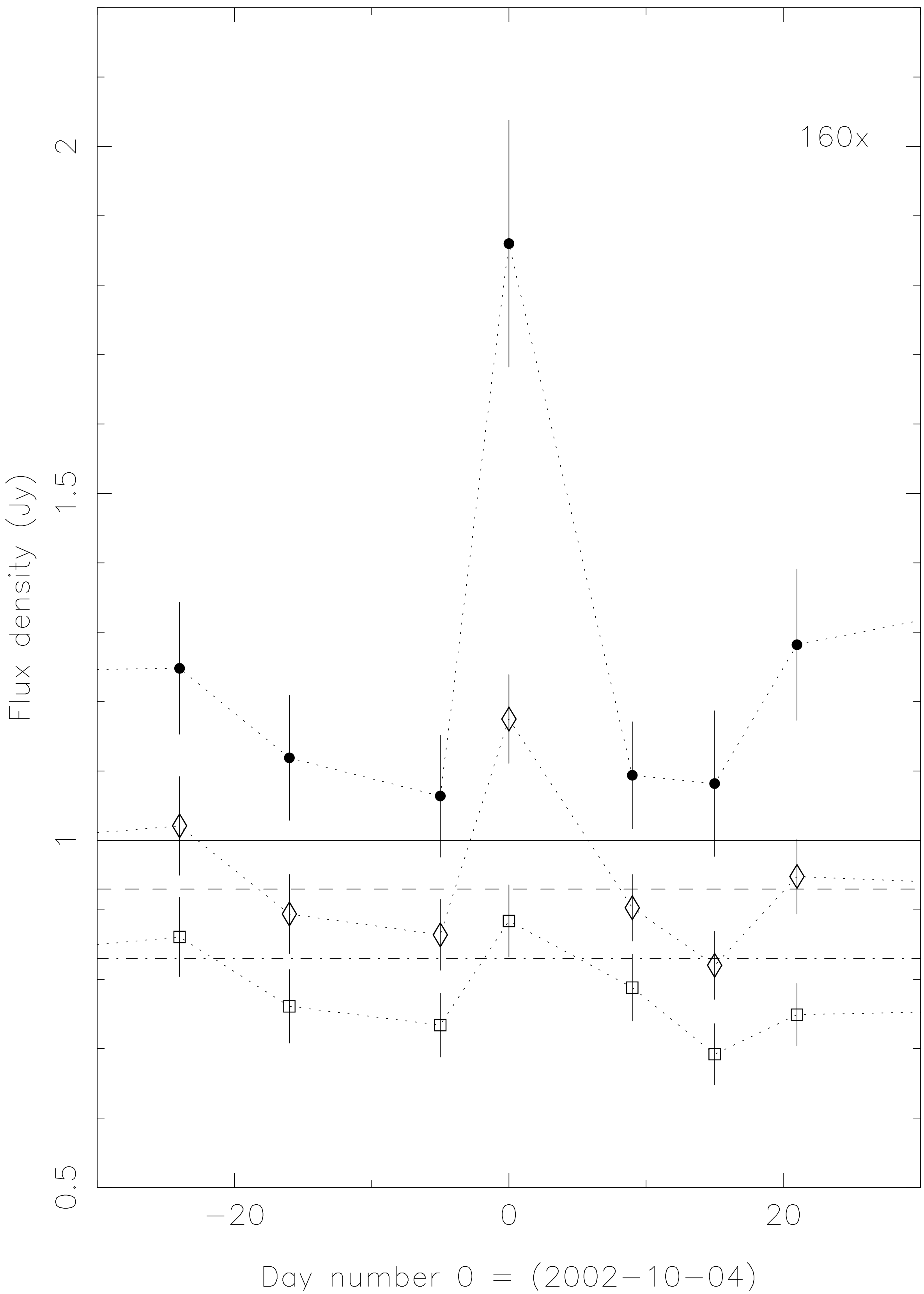
Fig. 1.— Top: The flux density measurements made from the VLA observations at 2 cm (open squares), 1.3 cm (open diamonds) and 7 mm (solid dots) 30 days before-and-after the 2002-10-03 X-ray flare. The error bars mark the 1σ uncertainty in the variability measurements. The horizontal lines (solid, dash, and dash-dot-dash) mark the mean values at 7 mm, 1.3 and 2 cm, respectively.

Fig. 2.— The flux density measurements made from the VLA observations at 2 (open squares), 1.3 cm (open diamonds) and 7 mm (solid dots) 30 days before-and-after the three X-ray flares detected on 2000-10-27 (Top), 2001-09-04 (Middle) and 2002-05-29 (Bottom). The horizontal lines (solid, dash, and dash-dot-dash) mark the mean values at 7 mm, 1.3 and 2 cm, respectively. The X-ray flares were observed with peak flux a factor of 20 greater than the value of the quiescent state. The error bars mark the 1σ uncertainty in the variability measurements. The origin of the horizontal axis corresponds to the date of each x-ray flare.


160x
Flux density (Jy)
2
1.5
1
0.5
−20
0
20
Day number 0 = (2002−10−04)

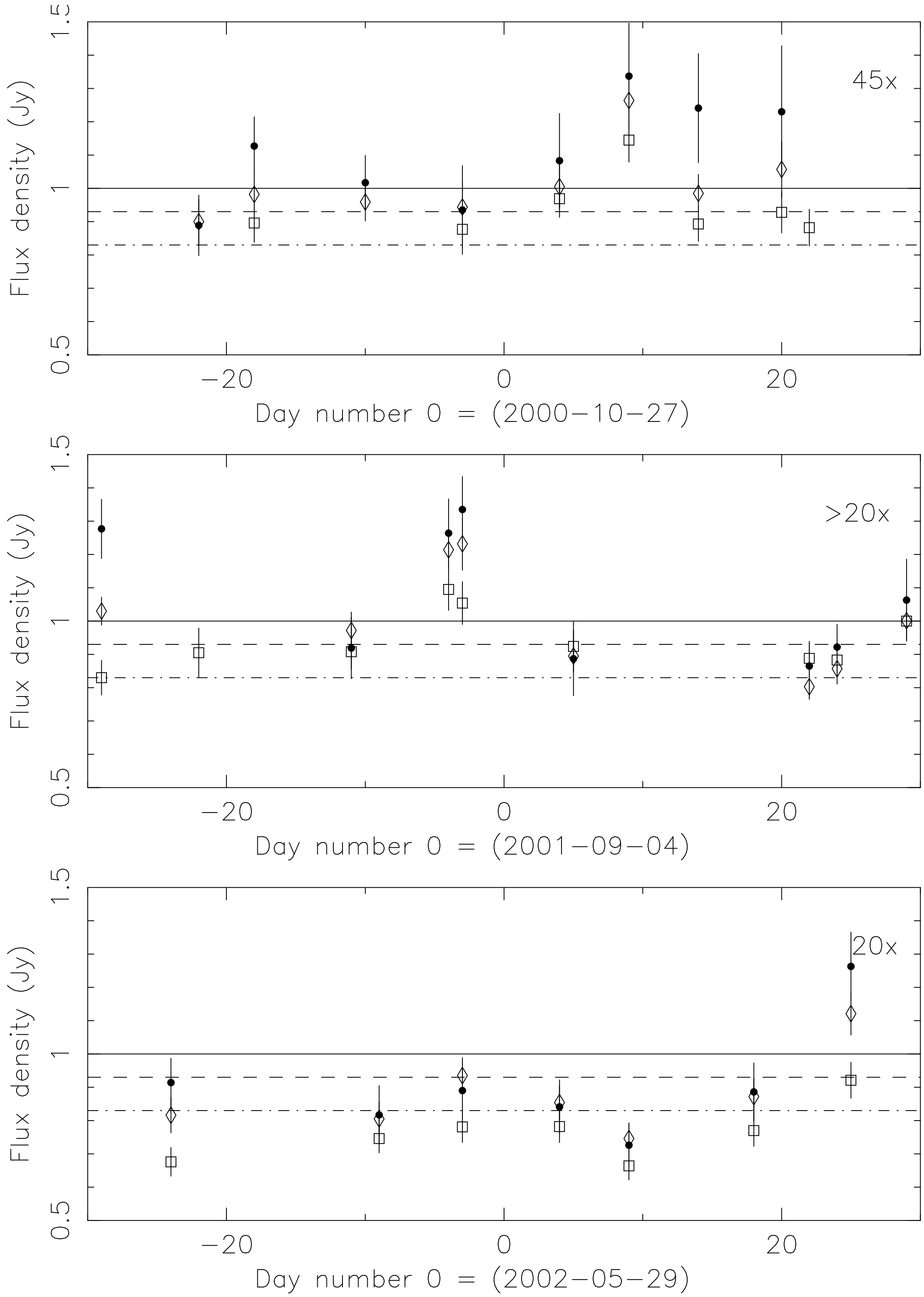

Flux density (Jy)
0.5
1
1.5
45x
−20
0
20
Day number 0 = (2000−10−27)
>20x
Day number 0 = (2001−09−04)
20x
Day number 0 = (2002−05−29)

Table 1. Radio Properties of The Outburst on 2002-10-03

λ (cm)	$< \mathrm{S} >$ (Jy)	$\mathrm{S_t}$ (Jy)	ΔS (Jy)
2.0	0.83±0.01	0.88±0.05	0.05±0.05
1.3	0.93±0.01	1.18±0.06	0.25±0.06
0.7	1.00±0.01	1.86±0.18	0.86±0.18
	α (S$\propto \nu^{\alpha}$)		
2.0/1.3/0.7	0.20±0.02	0.7±0.1	$2.4^{+0.3}_{-0.6}$